Electronic Supplementary Material (ESI) for Soft Matter.

Supporting Information: Metachronal patterns by magnetically-programmable artificial cilia surfaces for low Reynolds number fluid transport and mixing

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I. EXPERIMENTAL SET UP

In this paper we follow closely the experimental set-up of our previous work[1]. We therefore briefly summarize here the most important aspects of the experimental system. Ferromagnetic-elastic sheet-based artificial cilia were made of composite materials of silicone rubber, which has a density of $(2.00 \pm 0.056) \times 10^3 \mathrm{kg}/m^{-3}$ and an average Young's modulus of 144 kPa. A rotating Halbach array was used to generate a rotating uniform magnetic field, which was about 40 mT. The uniformity of the magnetic field in the workspace was ~ 95 % in the region that covered the whole artificial cilia array in the experiments. The artificial cilia array was fixed in a container filled with glycerol (99.8% volume ratio), which had a density of $1.257 \times 10^3 \mathrm{kg}/m^{-3}$ and a dynamic viscosity of 0.876 Pa·s at room temperature of 25°C.

II. MOVIES

The 6×6 cilia array has a pitch of $L_x = 1.75L$ and $L_y = 0.75W$ and the frequency is 1 Hz. The movies are played at 0.3 times the real speed, except Movie ESI 9 which is played at 1.5 times the real speed. Movies ESI 1 until ESI 9 contain an angled view, while movies ESI 10 to 14 contain top views emphasizing the metachronal wave propogation angle γ.

Movie ESI 1: Synchronous beating for $\Delta\varphi_x = 0$ and $\Delta\varphi_y = 0$.

Movie ESI 2: Antiplectic metachronal wave for $\Delta\varphi_x = -\pi/6$ and $\Delta\varphi_y = 0$.

Movie ESI 3: Symplectic metachronal wave for $\Delta\varphi_x = \pi/6$ and $\Delta\varphi_y = 0$.

Movie ESI 4: Laeoplectic metachronal wave for $\Delta\varphi_x = 0$ and $\Delta\varphi_y = \pi/6$.

Movie ESI 5: Laeoplectic metachronal wave for $\Delta\varphi_x = 0$ and $\Delta\varphi_y = \pi/2$.

Movie ESI 6: Laeoplectic metachronal wave for $\Delta\varphi_x = 0$ and $\Delta\varphi_y = 2\pi/3$.

Movie ESI 7: Antiplectic-laeoplectic metachronal wave for $\Delta\varphi_x = -\pi/6$ and $\Delta\varphi_y = \pi/6$.

Movie ESI 8: Symplectic-laeoplectic metachronal wave for $\Delta\varphi_x = \pi/6$ and $\Delta\varphi_y = \pi/6$.

Movie ESI 9: Antiplectic-laeoplectic metachronal wave for $\Delta\varphi_x = -5\pi/6$ and $\Delta\varphi_y = \pi/3$.

Movie ESI 10: Top view of antiplectic metachrony for $\gamma = \pi$ ($\Delta\varphi_x = -\pi/3$ and $\Delta\varphi_y = 0$).

Movie ESI 11: Top view of antiplectic-laeoplectic metachrony for $\gamma = 1.37\pi$ ($\Delta\varphi_x = -\pi/3$ and $\Delta\varphi_y = \pi/3$).

Movie ESI 12: Top view of symplectic metachrony for $\gamma = 0$ ($\Delta\varphi_x = \pi/3$ and $\Delta\varphi_y = 0$).

Movie ESI 13: Top view of symplectic-laeoplectic metachrony for $\gamma = 1.635\pi$ ($\Delta\varphi_x = \pi/3$ and

$\Delta\varphi_y = \pi/3$).

Movie ESI 14: Top view of laeoplectic metachrony for $\gamma = 1.5\pi$ ($\Delta\varphi_x = 0$ and $\Delta\varphi_y = \pi/3$).

III. FIGURES

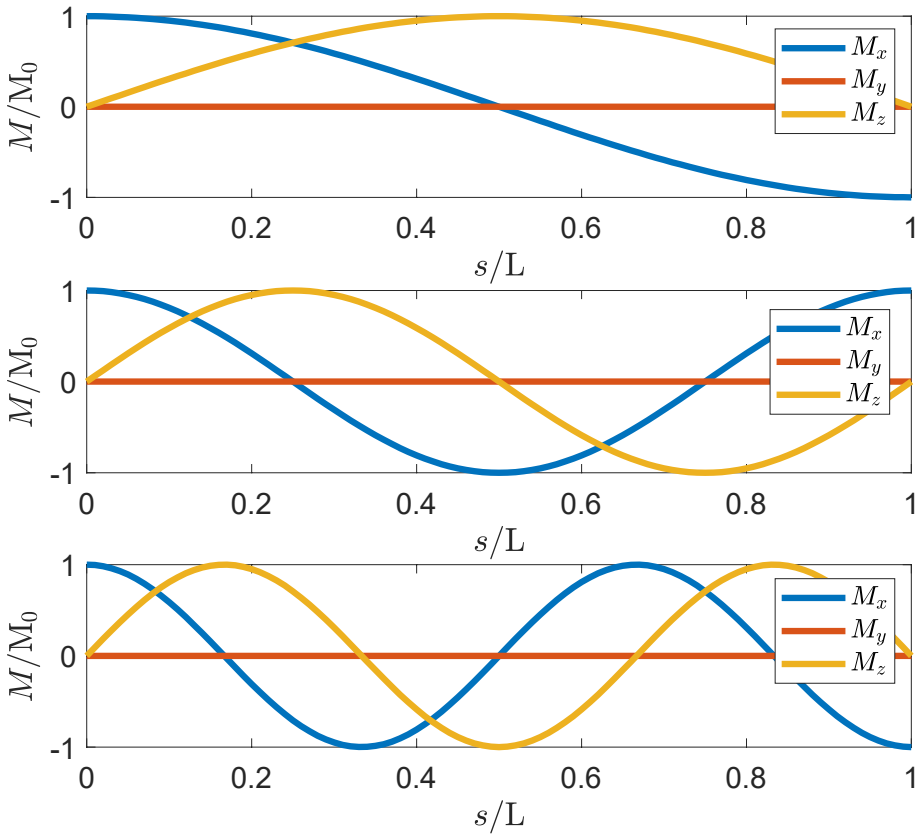

FIG. S1. The magnetization M/M_0 as a function of s/L for (a) $\alpha = \pi$, (b) $\alpha = 2\pi$ and (c) $\alpha = 3\pi$.

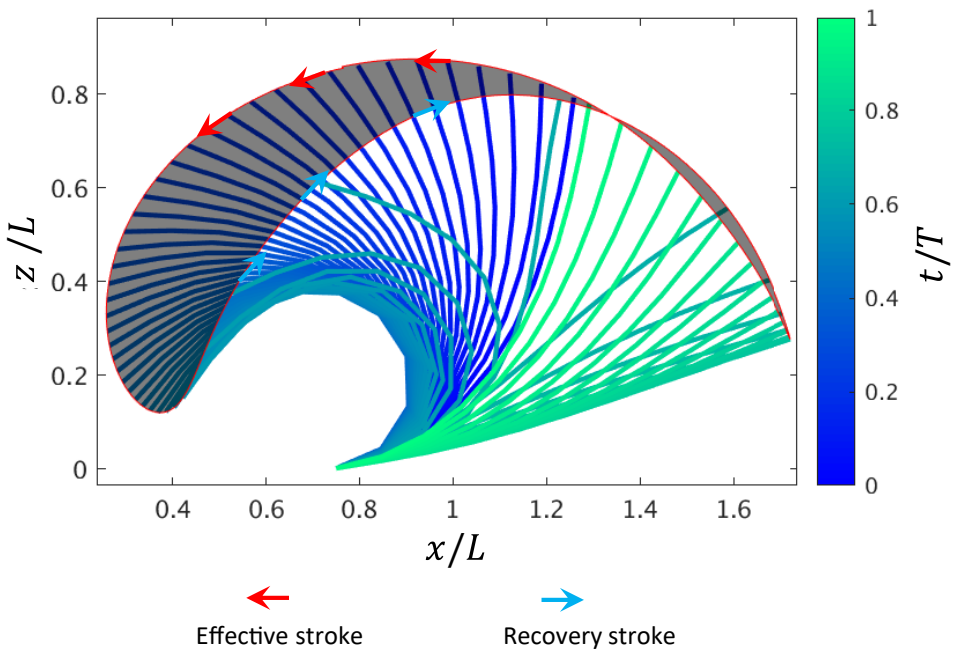

FIG. S2. A non-reciprocal cilium with effective stroke and recovery stroke. The grey area is the negative swept area (S_A) of the cilium tip in a full beating cycle T.

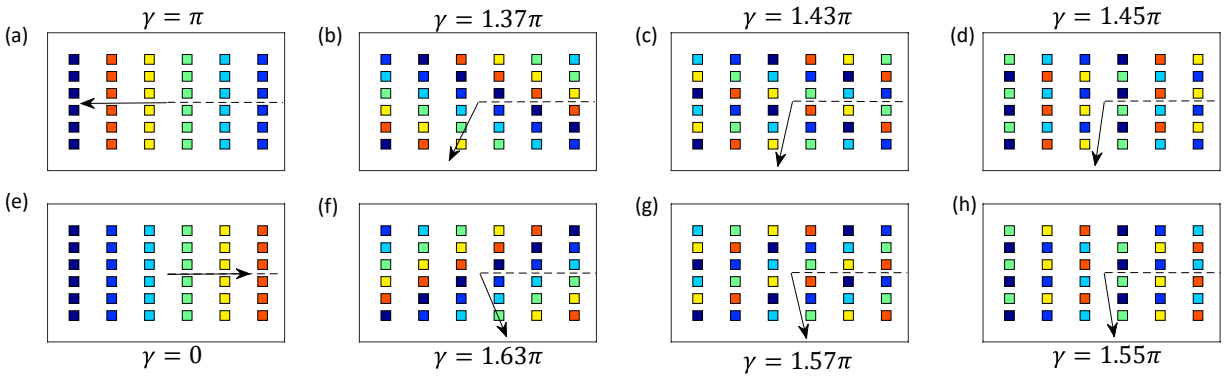

FIG. S3. The cilia beating patterns. (a) AM-LM wave for $\Delta\varphi_x=-\pi/3, \Delta\varphi_y=0$ with $\gamma=\pi$ (see movie ESI 10), (b) AM-LM wave for $\Delta\varphi_x=-\pi/3, \Delta\varphi_y=\pi/3$ with $\gamma=1.37\pi$ (see movie ESI 11), (c) AM-LM wave for $\Delta\varphi_x=-\pi/3, \Delta\varphi_y=2\pi/3$ with $\gamma=1.43\pi$, (d) AM-LM wave for $\Delta\varphi_x=-\pi/3, \Delta\varphi_y=\pi$ with $\gamma=1.45\pi$, (e) SM-LM wave for $\Delta\varphi_x=\pi/3, \Delta\varphi_y=0$ with $\gamma=0$ (see movie ESI 12), (f) SM-LM wave for $\Delta\varphi_x=\pi/3, \Delta\varphi_y=\pi/3$ with $\gamma=1.63\pi$ (see movie ESI 13), (g) SM-LM wave for $\Delta\varphi_x=\pi/3, \Delta\varphi_y=2\pi/3$ with $\gamma=1.57\pi$, (h) SM-LM wave for $\Delta\varphi_x=\pi/3, \Delta\varphi_y=\pi$ with $\gamma=1.55\pi$. The wave transform direction is dark blue, blue, light blue, green, yellow, red.

REFERENCES

[1]X. Dong, G. Z. Lum, W. Hu, R. Zhang, Z. Ren, P. R. Onck and M. Sitti, *Science Advances*, 2020, **6**, eabc9323.

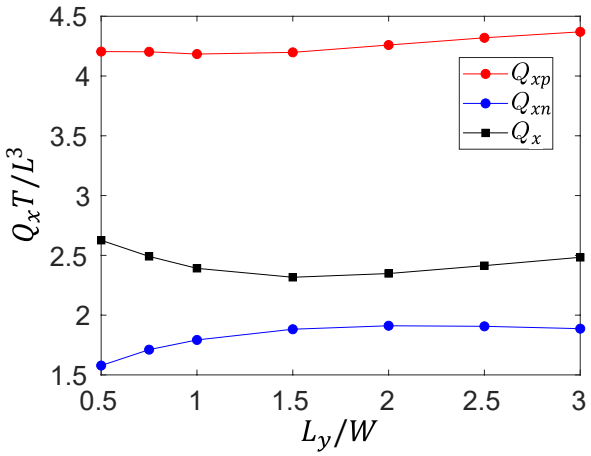

FIG. S4. Shielding effect on Q_x for L_x=4L as a function of cilia spacing L_y. Q_{xp} is the fluid volume in the effective stroke and Q_{xn} is the fluid volume in the recovery stroke during one beating cycle.